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Phosphorus Uptake and Use Efficiencies of Two Upland Rice (*Oryza sativa* L.) Varieties under Varying Phosphorus Rates and Seasons

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Abstract: Phosphorus (P) is an essential macronutrient for rice (*Oryza sativa* L.) production, yet its availability is often limited in tropical soils, constraining crop growth and yield. Optimizing phosphorus use efficiency (PUE) is crucial for enhancing rice productivity while minimizing fertilizer input costs. This study evaluates the yield and phosphorus use efficiencies of two upland rice varieties, Nerica 4 and Komboka, under different phosphorus application levels across two growing seasons (short and long rains) in Kenya. The findings provide insights into varietal differences in phosphorus acquisition and utilization, contributing to site-specific fertilizer recommendations for sustainable upland rice production. A field experiment was conducted using a randomized complete block design (RCBD) in a split-plot arrangement. The main plots consisted of two rice varieties, Nerica 4 and Komboka, while the sub-plots comprised four phosphorus application levels (0, 30, 50 and 70 kg P ha^{-1}), with three replications. Grain and stover yields were measured at harvest, and plant samples were collected for phosphorus analysis. Phosphorus use efficiencies, including agronomic efficiency, physiological efficiency, partial factor productivity, recovery efficiency, and internal utilization efficiency, were calculated. Nerica 4 exhibited significantly higher grain yield and phosphorus-use efficiency than Komboka. During the short rains, grain yield in Nerica 4 ranged from 2.34 t ha^{-1} (P0) to 5.75 t ha^{-1} (P70), while Komboka recorded yields between 1.97 t ha^{-1} (P0) and 3.5 t ha^{-1} (P70). In the long rains, grain yield in Nerica 4 ranged from 0.6 to 2.4 t ha^{-1}, whereas Komboka recorded yields between 0.6 and 1.85 t ha^{-1}. Additionally, Nerica 4 demonstrated significantly superior agronomic efficiency, partial factor productivity, and recovery efficiency compared to Komboka. Phosphorus application rates, rice variety and seasonal conditions significantly influenced rice yield, phosphorus uptake, efficiency, and overall plant performance. The findings highlight the importance of variety-specific phosphorus management strategies to enhance the productivity and sustainability of upland rice. Based on the results, an application rate of P 70 kg ha-1 is recommended for optimal yield and P 50 kg ha-1 for efficient nutrient use, and a cost-effective option with relatively good yields.

Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops globally, serving as a staple food for nearly half of the world's population (Himanshu et al., 2019; Paul et al., 2024; Das et al., 2024). It provides a significant portion of daily caloric intake for approximately 3.5 billion people (Samuel, 2019; Jamal et al., 2025; Njinju et al., 2018a). Over the years, rice consumption has steadily increased due to population growth, urbanization, and shifting dietary preferences. However, despite the expansion of rice cultivation worldwide, productivity gains have not kept pace with

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rising demand, creating a widening gap between production and consumption (Kijima et al., 2006; Balasubramanian et al., 2007; Ireri et al., 2019; Mishra et al., 2024; Pal et al., 2024; Priyadarshani et al., 2025).

The world rice demand in 2022/23 was 514.8 million tonnes against a production of 518.6 million tonnes. An 8.7 million-tonne rice deficit was noted, marking the largest in two decades, mainly due to extreme weather conditions and export restrictions (Business, 2023). In Sub-Saharan Africa (SSA), rice cultivation has rapidly expanded, establishing the crop as both a staple food and a commercial commodity (Kagito et al., 2023). From 1990 to 2018, rice production in SSA increased from 9.2 to 31.5 million tonnes, largely driven by the increased use of nitrogen (N) and phosphorus (P) fertilizers (USDA, 2018). Despite this progress, rice yields in SSA remain low, averaging 2.1 t ha^{-1}, compared to the global average of 4.8 t ha^{-1}, highlighting the need for productivity-enhancing strategies (Njinju et al., 2018b; Fróna et al., 2019).

In Kenya, the demand for rice has grown considerably due to urbanization and changing dietary preferences (Mati et al., 2011). In 2014, the country's rice production stood at 112,263 tonnes from about 28,390 hectares, fulfilling only 16% of national demand (FAO, 2016). Consequently, Kenya depends heavily on rice imports to bridge the consumption gap (Atera et al., 2018; Njinju et al., 2018a). To address this shortfall, there is a pressing need to expand the cultivated area and improve productivity per unit area. For instance, upland rice productivity in Kenya is approximately 1.0 t ha^{-1}, which is significantly lower than the regional potential of 7 t ha^{-1} (Magoti et al., 2019; Gweyi-Onyango, 2018). Identifying the main production constraints and applying targeted interventions are essential to increasing yields.

One of the major limitations in upland rice cultivation is phosphorus use efficiency (PUE) (Fageria et al., 2013). Phosphorus (P) is a crucial macronutrient that supports plant growth by enhancing root development, energy transfer, and overall productivity (Dobermann et al., 2000; Maitra et al., 2025a; Nasar et al., 2025). However, in many tropical regions, phosphorus availability is constrained due to its fixation in acidic and highly weathered soils, posing a major challenge to upland rice production (Sanchez, 2019; Chepkorir et al., 2024). Effective phosphorus management is vital for optimizing yields, reducing fertilizer costs, and minimizing environmental impacts from overuse (Tilman et al., 2021; Ray et al., 2025). PUE, defined as the yield increase per unit of applied phosphorus, depends on factors such as the phosphorus source, application rate, environmental conditions, and crop genotype (Kumar et al., 2002; Shao et al., 2025; Gitari et al., 2020). Both fertilizer type and environmental conditions significantly influence phosphorus availability; excess application can lead to water pollution while deficiency hinders food production (Jupp et al., 2021). Therefore, aligning phosphorus inputs with crop needs is essential for improving soil fertility and achieving sustainable rice production.

Despite widespread fertilizer use, plants typically utilize only 10–30% of applied phosphorus within a single growing season (Syers et al., 2008; Mukesh et al., 2024; Githumbi et al., 2025), with residual phosphorus from previous applications playing a significant role in long-term productivity (Sattari et al., 2012; Sairam et al., 2025). Enhancing crop efficiency in utilizing residual phosphorus is a promising strategy for improving sustainability (Ahmad et al., 2025; Nduwimana et al., 2020; Ochieng et al., 2021). The development of phosphorus-efficient rice varieties capable of thriving in low-input systems while minimizing fertilizer dependency in high-input systems is therefore critical (Deng et al., 2018).

Given the pressing need for sustainable rice production, this study evaluates the phosphorus use efficiencies of two upland rice varieties under different phosphorus levels across two growing seasons in Kenya. By examining variety-specific responses to phosphorus application and seasonal variations, the findings will contribute to the development of targeted nutrient management strategies. Identifying optimal phosphorus rates and efficient rice cultivars will not only enhance productivity and reduce input costs for farmers but also promote long-term sustainability in rice production.

Materials and Methods

Study area

The research study was carried out over two planting seasons at Kirogo farm, Kimbimbi Mwea, in Kirinyaga County, in the central part of Kenya. The first season ran from September to December during the 2020 short rains, while the second planting season ran from March to June during the 2021 long rains. Kenya Agricultural and Livestock Research Organization (KALRO-Mwea) Kirogo farm is located at 0°37′S, 37°20′ E, and 1159 m above sea level. Rainfall pattern ranges from 500 to 850 mm per annum. The temperatures range between 15.4°C and 29.5°C (Gweyi et al., 2021). The soils are nitisols, deep, well-drained, dusky-red to dark reddish-brown friable clays with low fertility (Njinju et al., 2018b).

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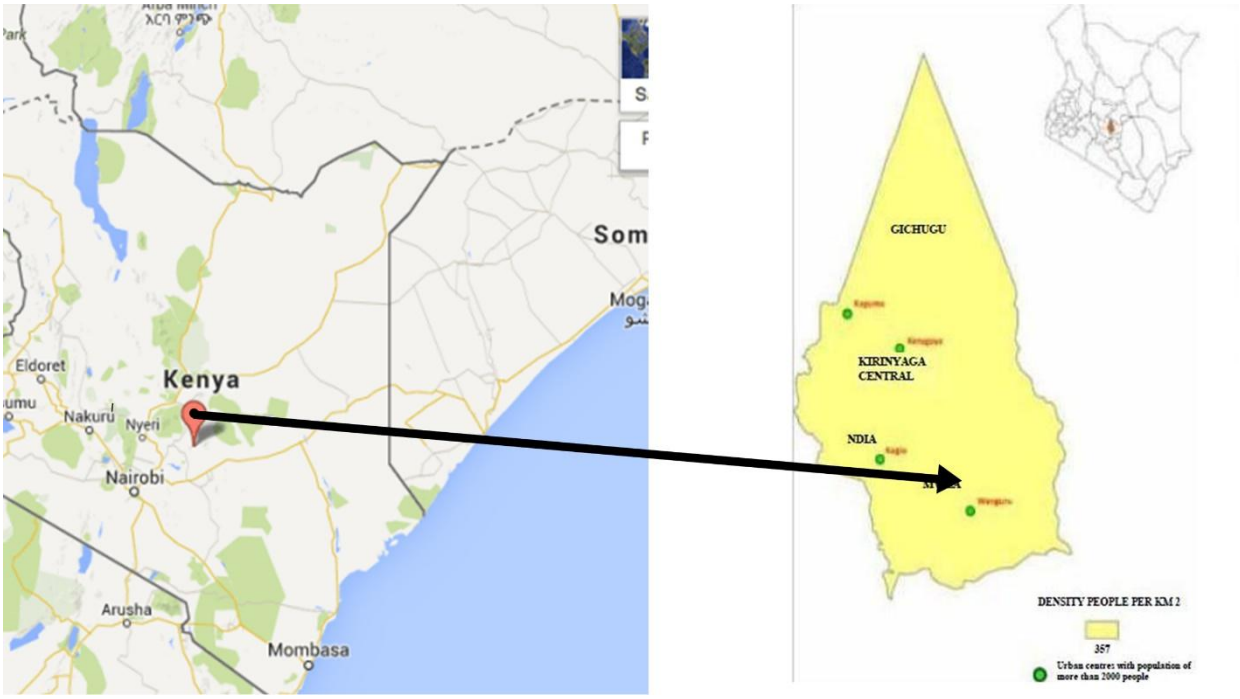

Figure 1. Map of Mwea in Kirinyaga County.

Treatment and experimental design

The trial was established at Mwea. Calcium Ammonium Nitrate (CAN) 75 kg/ha was applied 10 days after planting for the provision of nitrogen, and Muriate of potash 50 kg/ha was applied to maintain N and K levels as constant. The experiment was laid out on a randomized complete block Design (RCBD) in a split-plot arrangement. The main plots were two rice varieties, and the subplots were the P levels, which were as follows;

1. Control- No inputs (No fertilizer)
2. 30kg/ha of triple super phosphate
3. 50kg/ha of triple super phosphate
4. 70kg/ha of triple super phosphate

Plot sizes of 4.0m by 4.0 m were marked, and guard rows were created with 0.5 m spacing after tillage. There were 24 plots. Planting was done at the onset of the rainy season using recommended agronomic practices. The seeding rate was 3 to 4 seeds per hole, and thinning was done at a spacing of 20cm by 15 cm 2 weeks after emergence. Pests, weeds, diseases, and cultural management practices were done during the season.

Crop establishment and field management

Planting was done at the onset of the rains. A seeding rate of 3 to 4 seeds per hole was used, and the seedlings were thinned to achieve inter- and intra-row spacing of 20 and 15 cm, respectively, 2 weeks after emergence. Calcium Ammonium Nitrate (CAN) was applied at a rate of 75 kg/ha across all plots 10 days after planting to provide nitrogen. Muriate of Potash (MOP) at the rate of 50 kg/ha was applied to maintain constant levels of nitrogen (N) and potassium (K). Other agronomic practices, such as pest, weed, and disease management, were carried out as and when required.

Soil sampling and analysis

At the start of the 2 seasons before planting, five soil samples were collected from 0-25cm deep before planting and put in plastic bags for sampling.

• Soil pH was determined in water (1:2 soil: water) using a pH meter

• Mehlich1 extracting solution (0.0125 M H_2SO_4+0.05M HCl), also referred to as dilute double acid. Using a graduated cylinder, 167 ml of concentrated HCl (1.2M) and 28 ml of concentrated H_2SO_4 (1.8M) were added to approximately 35l of de-ionized water in a large polypropylene carboy container. The mixture was made to a final volume of 40L by adding de-ionized water. Bubbling of air through the solution for 3 hours was done to ensure a homogenous solution was obtained. 5gms of sieved and air-dried soil sample was poured into a 50ml extraction flask. 200mg of charcoal was added to each flask in order to obtain a colorless filtrate, followed by the addition of 20ml of the Mehlich 1 extracting solution and shaking for five minutes on a reciprocating shaker set at a minimum of 180 rpm at room temperature.

Table 1 clearly shows that the soil composition during the short-rain season had low extractable N, moderate available P, and moderate exchangeable K, while the pH was neutral. For the long rains season, as highlighted, there was low extractable N, low available P, and moderate exchangeable K, and the pH was neutral in both soil analyses.

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Table 1. Soil composition during the short (2020) and long rains (2021) season.

Season	Soil components	Value
Short rains	Extractable N	0.006
	Available P	33.17
	Exchangeable K	138.8
	Soil PH	7.1
Long rains	Extractable N	0.018
	Available P	23.4
	Exchangeable K	64.5
	Soil PH	6.9

Data analysis

The collected data were subjected to analysis of variance (ANOVA) and analyzed in R. Treatment means were separated at P<0.05. Correlation was done on the efficiencies and P content in the vegetative and reproductive parts.

Results

Yield

Yields were higher during the short rains than the long rains. The difference was due to the low rainfall received during the long rains.

Yields ranged from 2.34 t ha^{-1} and 5.75 t ha^{-1} for the Nerica 4 variety and 1.97 t ha^{-1} - 3.5 t ha^{-1} for the Komboka variety. The varieties and P levels recorded a significant interaction during the short rains (Table 2). Nerica 4 obtained the highest mean of 5.75 t ha^{-1} and 5.0 t ha^{-1} at P70 and P50, respectively. Komboka, on the other hand, obtained 3.5 t ha^{-1} and 2.8 t ha^{-1} at the same level. P70 recorded higher means of 4.62 and Nerica 4 had significantly higher means of 4.62 t ha^{-1} compared to Komboka. Stover yield ranged between 3.71-6.98 t ha^{-1} in Nerica 4, and Komboka recorded a range of 3.78-5.73 t ha^{-1}. Additionally, P70 recorded a significant mean of 6.05 t ha^{-1}. A significant interaction between variety and phosphorus was also noted for the harvest index, with Nerica at P50 and Komboka at P70 recording a mean of 0.45 t ha^{-1}. Komboka recorded a higher mean of 0.44 t ha^{-1} compared to Nerica 4. P30 and P50 recorded the highest mean of 0.44 t ha^{-1} in comparison to the other P levels.

During the long rains (Table 3), a significant interaction between varieties and P levels was observed. Grain yields ranged from a mean of 0.6 to 2.4 t ha^{-1} in Nerica varieties, while they ranged from 0.6 to 1.85 t ha^{-1} in the Komboka variety. At P70, Nerica 4 and Komboka recorded higher means of 2.4 t ha^{-1} and 1.85 t ha^{-1}, respectively. P70 recorded a significant mean of 2.13 compared to other P levels.

Stover yield ranged between 1.3-3.1 t ha^{-1} in the Nerica variety, and for Komboka, the means ranged from 1.2-2.55t ha^{-1}. P70 recorded a higher mean of 2.83, while Nerica 4 recorded a significant interaction with P70 at a mean of 3.1 t ha^{-1}

Harvest index for the Nerica variety ranged between 0.42 and 0.64, while in Komboka it ranged between 0.42 and 0.67. The highest means in the interaction between varieties and Komboka were recorded at P70 at 0.64 and 0.67 for Nerica 4 and Komboka, respectively. P70 recorded a higher mean of 0.66, with Komboka recording a higher mean of 0.6. Phosphorus harvest index ranged between 0.9-0.51 for Nerica and 0.3-0.48 for Komboka. Significant means of 0.51 were recorded in the interaction between varieties and P levels at P50 and P70.

The highest means of Phosphorus harvest index were recorded at P70, P50, and P30. Similar to the yields, there was a significant interaction of varieties and P levels, with P70 recording the highest harvest index of 0.66. Overall, the Komboka variety recorded the highest harvest index of 0.6.

Table 2. Yield and harvest index at harvest during short rains as affected by phosphorus rates in two rice varieties.

Varieties	T levels	Grain yield (T/ha)	Stover yield (T/ha)	Phosphorus Harvest index	Harvest index
Nerica 4	P_0	2.34^{e}	3.71	0.14	0.34^{e}
	P_{30}	4.32^{bc}	5.68	0.17	0.43^{c}
	P_{50}	5^{ab}	5.35	0.14	0.45^{a}
	P_{70}	5.75^{a}	6.98	0.15	0.42^{d}
Komboka	P_0	1.97^{e}	3.78	0.25	0.42^{d}
	P_{30}	2.5^{de}	5.23	0.16	0.45^{a}
	P_{50}	2.8^{de}	5.73	0.16	0.44^{b}
	P_{70}	3.5c^{d}	5.13	0.17	0.45^{a}
LSD		1.02	1.66	0.08	0.003
V*T		*	0.23	0.19	***
	P_0	2.16^{c}	3.75^{b}	0.2	0.38^{c}
	P_{30}	3.41^{b}	5.45^{a}	0.17	0.44^{a}
	P_{50}	3.9^{b}	5.54^{a}	0.15	0.44^{a}
	P_{70}	4.62^{a}	6.05^{a}	0.16	0.43^{b}
LSD		0.72	1.17	0.06	0.002
Treatment (T)		***	**	0.38	***
Nerica 4		4.35^{a}	5.43	0.15	0.41^{b}
Komboka		2.69^{b}	4.97	0.19	0.44^{a}
LSD		0.51	0.83	0.04	0.001
Variety (V)		***	0.26	0.07	***

Key: ***=very highly significant; **=highly significant, *=significant; ns=not significant; T levels=Phosphorus treatment levels.

Table 3. Yield and harvest index at harvest during long rains as affected by phosphorus rates in two rice varieties.

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Varieties	T levels	Grain yield (T/ha)	Stover yield (T/ha)	Phosphorus Harvest Index	Harvest index
Nerica 4	P_0	0.6^{d}	1.3^{d}	0.19^{d}	0.42^{d}
	P_{30}	0.8^{d}	1.5^{d}	0.3^{cd}	0.42^{d}
	P_{50}	1.9^{b}	2.6^{b}	0.51^{a}	0.61^{c}
	P_{70}	2.4^{a}	3.1^{a}	0.51^{a}	0.64^{b}
Komboka	P_0	0.5^{d}	1.2^{d}	0.3^{cd}	0.42^{d}
	P_{30}	1.25^{c}	1.95^{c}	0.48^{ab}	0.66^{a}
	P_{50}	1.8^{b}	2.5^{b}	0.44^{abc}	0.66^{a}
	P_{70}	1.85^{b}	2.55^{b}	0.36^{bc}	0.67^{a}
LSD		0.42	0.42	0.15	0.02
V*T		*	*	*	***
	P_0	0.55^{c}	1.25^{c}	0.25^{b}	0.42^{d}
	P_{30}	1.03^{b}	1.73^{b}	0.39^{a}	0.54^{c}
	P_{50}	1.85^{a}	2.55^{a}	0.48^{a}	0.63^{b}
	P_{70}	2.13^{a}	2.83^{a}	0.44^{a}	0.66^{a}
LSD		0.3	0.3	0.11	0.01
Treatments(T)		***	***	**	***
Nerica 4		1.43	2.13	0.38	0.52^{b}
Komboka		1.35	2.05	0.4	0.6^{a}
LSD		0.21	0.21	0.08	0.008
Variety (V)		0.45	0.45	0.62	***

Key: ***=very highly significant, **=highly significant, *=significant, ns=not significant
T levels=Phosphorus treatment levels

P-uptake in grains and stover of two rice varieties under different P rates

Results revealed that P uptake in grains and stover parts differed significantly among the treatments across the two seasons. During the short rains (Table 4), Nerica 4 recorded significantly higher P uptake in stover compared to Komboka. Additionally, treatment means differed significantly across P levels, with P70 performing best. It was noteworthy that there were interactions of the varieties with the treatments. During the long rains, Nerica 4 had significantly higher grain and stover uptake means than Komboka. The treatments differed significantly, with the highest means recorded for P70. In grain and stover uptake, the varieties exhibited different responses to P levels, with observed interactions.

During the short rains (Table 4), an interaction of the varieties and P levels was observed in stover P uptake, with Nerica at P70 recording the highest mean of 41.88. P levels had a significant difference in P uptake in stover, with P70 recording means of 35.75 t ha^{-1}. P uptake in stover had significantly higher means of 32.30 t ha^{-1} in Nerica 4 compared to Komboka's mean of 23.16 t ha^{-1}. P levels recorded higher means of 52.8 t ha^{-1}at P70 in Total P uptake. During the long rains (Table 4), a significant interaction between varieties and P levels was observed in P uptake in grain and stover. Grain P uptake differed significantly across the P levels means. Nerica 4 recorded the highest grain P uptake, 10.29 t ha^{-1} at P70, while Komboka recorded significantly higher means of 6.88 t ha^{-1} at P30. P uptake interaction in stover yield showed a significant difference at P50, with a mean of 7.86 t ha^{-1} in Nerica 4. P50 had significantly higher P uptake in stover and total P uptake with means of 7.86 t ha^{-1} and 6.98 t ha^{-1}, respectively. P70 recorded a higher mean of 18.5 t ha^{-1} in total P uptake.

Table 4. P-uptake in stover and grains for Nerica-4 and Komboka short and long rains planting seasons.

Varieties	T (levels)	Grain Uptake (T/ha)	Stover Uptake (T/ha)	TotalP uptake (T/ha)	Grain Uptake (T/ha)	Stover Uptake (T/ha)	TotalP uptake T/ha)
		Short rains			Lond rains		
Nerica 4	P_0	3.53	20.05^{g}	24.7	1.77^{e}	6.38^{d}	9.89
	P_{30}	6.91	29.8^{c}	41	3.91^{cde}	7.23^{c}	12.99
	P_{50}	6.65	37.48^{b}	49.6	9.13^{ab}	7.86^{a}	17.66
	P_{70}	8.52	41.88^{a}	55.7	10.29^{a}	7.59^{b}	20.29
Komboka	P_0	6.74	13.78^{h}	27	1.97^{de}	4.59^{g}	6.43
	P_{30}	6.08	22.96^{f}	40.5	6.88^{abc}	5.17^{f}	14.54
	P_{50}	6.85	26.28^{e}	44.6	6.66^{bc}	6.09^{e}	15.85
	P_{70}	7.98	29.63^{d}	49.8	5.45^{cd}	6.34^{d}	17.01
LSD		3.2	0.05	13.6	3.52	0.05	7.05
V*T		0.25	***	0.78	*	***	0.69
	P_0	5.14	16.91^{d}	2.59^{c}	1.87^{c}	5.48^{c}	8.16^{b}
	P_{30}	6.5	26.38^{c}	40.7^{b}	5.39^{b}	6.20^{b}	13.76^{a}
	P_{50}	6.75	31.88^{b}	47.1^{ab}	7.9^{a}	6.98^{a}	16.76^{a}
	P_{70}	8.25	35.75^{a}	52.8^{a}	7.87^{ab}	6.97^{a}	18.65^{a}
LSD		2.26	0.03	9.62	2.49	0.03	5.0
Treatments (T)		0.07	***	***	***	***	**
Nerica 4		6.4	32.30^{a}	42.8	6.28	7.26^{a}	15.21
Komboka		6.91	23.16^{b}	40.5	5.24	5.55^{b}	13.46
LSD		1.6	0.02	6.8	1.76	0.02	3.53
Variety (V)		0.50	***	0.48	0.23	***	0.31

Key: ***=very highly significant, **=highly significant, *=significant, ns=not significant
Kg/ha-Kilogram/hectare, P uptake –Phosphorus uptake, T levels=Phosphorus treatment levels.

Comparison of the P-Use Efficiencies (PUE) of Nerica-4 and Komboka rice varieties under different P rates.

Results revealed that P efficiencies, Agronomic

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efficiency, Partial factor productivity, Recovery efficiency, internal use efficiency, and Physiological efficiency differed significantly among the treatments across the seasons.

During the short rains (Table 5), Nerica 4 had significantly higher means than Komboka for agronomic efficiency, partial factor productivity, and recovery efficiency. The treatments differed significantly, with P30 recording higher means for partial factor productivity and recovery efficiency. P70 had significantly higher means than the other P levels for internal use efficiency and physiological efficiency. During the long rains season (Table 6), internal use efficiency and physiological efficiency had significantly higher means in Komboka than in Nerica 4. The treatments showed significant differences, with the highest means at P50 for agronomic efficiency, partial factor productivity, and physiological efficiency. Similarly, in internal use, significantly higher efficiency means were recorded at P70. In both seasons, the varieties responded differently to P levels, with significant interactions between varieties and P levels.

During the short rains (Table 5), Nerica 4 at 50kg/ha recorded a significantly higher mean of in agronomic efficiency 63.25 in comparison to Komboka. No significant difference was noted in Komboka; the means ranged from 21.75 to 24.11. A significant difference was observed in the varieties, with Nerica 4 recording a mean of 56.62. During the long rains (Table 6), there was no significant difference between the varieties, but an interaction between the varieties and P levels was noted, with Nerica 4 at 50kg/ha and 70kg/ha recording means of 26 and 22.76, respectively. Komboka significantly higher means were recorded at 50kg/ha at 23. P levels recorded significantly higher means of 24.5 at P50. Agronomic efficiency ranged from 14-63 kg/ha.

The partial factor productivity recorded during the short rains (Table 5) showed there were significant differences. Interactions between the varieties and P levels had significantly higher means of 152.5 at 30kg/ha in Nerica 4 and 91.7 at 30kg/ha in Komboka. During the long rains (Table 6), varieties and P levels had significantly higher means of 38 at 50kg/ha in Nerica 4 and 41.7 at 30kg/ha in Komboka. The partial factor productivity recorded during the short rains showed that the interaction between the varieties and treatments differed significantly by 152.5 at 30kg/ha in Nerica 4 and 91.7 at 30kg/ha in Komboka. The long rains recorded significantly higher means of 38 at 50kg/ha in Nerica 4 and 41.7 at 30kg/ha in Komboka.

During the short rains (Table 5), recovery efficiency differed significantly among treatments, with P30 recording a mean of 59.1. Significantly higher means were recorded at 30kg/ha. Nerica 4 recorded a mean of 64, and Komboka recorded a mean of 53.9. Komboka. During the long rains (Table 6), the interaction between the varieties and the treatments had significantly higher means. A range of 14.12-14.16 was recorded at 50kg/ha and 70kg/ha in Nerica 4, and 30kg/ha was recorded at a mean of 22.78 in Komboka.

During short rains (Table 5), Physiological efficiency interactions between varieties and P levels had significantly higher means of 140.43 and 102.38 at 70kg/ha in Nerica 4 and Komboka, respectively. Significant difference was noted among the treatments with a mean of 121.4 at P70. The varieties were significantly different, with Nerica 4 recording 129.15. Significantly higher means of 140.43 were recorded in Nerica 4 at 70kg/ha, and the lowest in Komboka at 30kg/ha at 36.05. During the long rains (Table 6), a significant difference was observed between the interactions of P levels and varieties. The highest means of 282.5 recorded in Komboka at 50kg/ha and 228.5 in Nerica 4 at 70kg/ha. P levels differed significantly, with P50 having a higher mean of 242.6. Additionally, Komboka recorded a significantly higher mean of 201.67 compared to Nerica. Significantly higher means of 282.5 were recorded in Komboka at 50kg/ha, and the lowest mean of 127.5 was recorded in Nerica 4 at 30kg/ha.

During the short rains (Table 5), there was a significant difference in P levels, significantly higher internal utilization efficiency (IE), with a mean of 101.9 recorded at P70. Nerica 4 recorded a mean of 103.9, which was considerably higher than Komboka. During the long rains (Table 6), an interaction between the varieties and P levels was observed. Significantly higher means of 102.5 and 152.9 were recorded at P70 in Nerica and Komboka, respectively. The means were significantly different, with 127.9 obtained in Komboka. In Internal utilization efficiency (IE) across the treatments in the short rains, Nerica 4 had a range of 99.5-112.1.

Discussion

This study underscores the significant impact of phosphorus (P) fertilization on grain yield, stover yield, and nutrient uptake in upland rice across both short and long rain seasons. The observed strong interactions between rice varieties and phosphorus levels highlight the differential genotypic responses to P application. Among the tested genotypes, Nerica 4 consistently demonstrated superior yield performance and phosphorus uptake efficiency compared to Komboka. These findings are consistent with previous research, which has shown that phosphorus enhances rice productivity by stimulating root development and nutrient assimilation (Dobermann et al., 2000; Sahoo et al., 2024; Fageria et al., 2011).

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The interplay between phosphorus levels and rice genotypes significantly influenced critical agronomic parameters, including grain yield, stover yield, harvest index, phosphorus uptake, and phosphorus use efficiencies. The varying responses between Nerica 4 and Komboka under different phosphorus rates and seasonal conditions emphasize the complex interactions between genotype and environment. This highlights the importance of selecting appropriate genotype fertilizer combinations to optimize yield and resource use efficiency, particularly in nutrient-limited rain-fed systems.

Table 5. P-use efficiencies for Nerica-4 and Komboka during the short-rains planting season.

Varieties	T levels	AE (kg grain/kg of P applied)	PFP (kg grain/kg of P applied)	RE%	PE (kg grain/kg of P uptake)	IE (kg grain/kg of P uptake)
Nerica 4	P_0	0	0	0	0	0
	P_{30}	52.5^{b}	152.5^{a}	64.4^{a}	113.36^{c}	100.1^{a}
	P_{50}	63.25^{a}	110^{b}	39.9^{a}	133.65^{b}	99.5^{a}
	P_{70}	54.11^{b}	76.8^{d}	38.2^{a}	140.43^{a}	112.1^{a}
Komboka	P_0	0	0	0	0	0
	P_{30}	22.92^{c}	91.7^{c}	53.9^{a}	36.05^{f}	53.9^{a}
	P_{50}	21.75^{c}	49^{e}	45.7^{a}	47.26^{e}	53.5^{a}
	P_{70}	24.11^{c}	53.6^{e}	26.8^{a}	102.38^{d}	91.7^{a}
LSD		6.21	12.99	13.01	5.78	16.8
V*T		*	***	0.11	***	0.06
	P_0	0	0	0	0	0
	P_{30}	37.71	122.1^{a}	59.1^{a}	74.71^{c}	77^{b}
	P_{50}	42.5	79.5^{b}	42.8^{b}	90.46^{b}	76.5^{b}
	P_{70}	39.11	65.2^{c}	32.5^{c}	121.4^{a}	101.9^{a}
LSD		4.34	9.19	9.2	4.09	11.88
T		0.09	***	*	***	***
Nerica 4		56.62^{a}	113.1^{a}	47.5	129.15^{a}	103.9^{a}
Komboka		22.92^{b}	64.7^{b}	42.1	61.9^{b}	66.4^{b}
LSD		3.58	7.5	7.51	3.34	9.7
V		***	***	0.14	***	***

Key: ***=very highly significant; **=highly significant; *=significant; ns-not significant; AE-Agronomic efficiency; PFP-Partial factor productivity; RE-Recovery efficiency; PE-Physiological efficiency; IE-Internal utilization efficiency; T levels=Phosphorus treatment levels.

Table 6. P-use efficiencies for Nerica-4 and Komboka in the long rains planting season.

Varieties	T levels	AE(kg grain/kg of P applied)	PFP(kg grain/kg of P applied)	RE%	PE(kg grain/kg of P uptake)	IE(kg grain/kg of P uptake)
Nerica-4	P_0	0	0	0	0	0
	P_{30}	14.17^{d}	26.7^{c}	7.92^{b}	127.5^{f}	69.1^{d}
	P_{50}	26^{a}	38^{ab}	14.12^{b}	202.42^{c}	100^{c}
	P_{70}	22.76^{ab}	30^{bc}	14.46^{b}	228.5^{b}	102.5^{c}
Komboka	P_0	0	0	0	0	0
	P_{30}	20.83^{bc}	41.7^{a}	22.78^{a}	175^{d}	107.2^{c}
	P_{50}	23^{ab}	36^{ab}	10.72^{b}	282.5^{a}	123.7^{b}
	P_{70}	19.29^{c}	26.4^{c}	12.5^{b}	147.5^{e}	152.9^{a}
LSD		3.35	8.31	7.192	5.37	10.1
T*V		***	*	**	***	**
	P_0	0	0	0	0	0
	P_{30}	17.5^{c}	34.2^{a}	15.35	151.25^{c}	88.1^{c}
	P_{50}	24.5^{a}	37^{a}	12.42	242.46^{a}	111.9^{b}
	P_{70}	21.02^{b}	28.2^{b}	13.48	188^{b}	127.7^{a}
LSD		2.37	5.88	5.09	3.8	7.14
Treatments(T)		***	*	0.46	***	***
Nerica 4		20.98	31.6	12.17	186.14^{b}	90.4^{b}
Komboka		21.04	34.7	15.33	201.67^{a}	127.9^{a}
LSD		1.93	4.8	4.15	3.10	5.83
Varieties(V)		0.94	0.18	0.12	***	***

Key: ***=very highly significant; **=highly significant; *=significant; ns-not significant; AE-Agronomic efficiency; PFP-Partial factor productivity; RE-Recovery efficiency; PE-Physiological efficiency; IE-Internal utilization efficiency; T levels=Phosphorus treatment levels.

Grain yield, a key measure of crop productivity, was significantly influenced by both phosphorus rate and variety. Nerica 4 outperformed Komboka across all phosphorus levels, with the highest yields recorded at 50 and 70 kg P ha^{-1}, which were statistically similar. These results align with Dobermann et al. (2000), who found that phosphorus application boosts grain yield, especially under conducive environmental conditions. The robust yield performance of Nerica 4 is attributed to its genetic traits that enhance nutrient uptake and utilization. Additionally, favorable moisture availability during the short rains further enhanced nutrient absorption (Haefele et al., 2008).

Stover yield also reflected significant varietal differences, with Nerica 4 producing greater biomass, particularly under elevated phosphorus levels. This suggests that Nerica 4 has greater vegetative vigor and

capacity for biomass accumulation, crucial traits for overall plant growth and resilience. Enhanced phosphorus availability promotes vegetative development, which translates into higher stover yield and overall crop performance.

In contrast, the harvest index (HI), representing the ratio of grain to total biomass, was higher in Komboka. This indicates more efficient assimilation partitioning to grain production relative to vegetative parts. Fageria et al. (2010) and Majeed et al. (2023) attributed such nutrient partitioning differences to genetic variability. Notably, the highest HI was recorded at 50 kg P ha^{-1}, suggesting that moderate phosphorus inputs can optimize both grain production and resource use, whereas excessive P does not necessarily enhance grain allocation (Maitra et al., 2022).

Seasonal differences further influenced the HI, with the long rains season showing higher HI values. This can be explained by more consistent rainfall and adequate moisture throughout critical growth stages such as flowering and grain filling, which improve assimilate partitioning to grains (Psiwa et al., 2022; Bouman et al., 2007; Cheptoek et al., 2021). In contrast, the short rains, often marked by irregular moisture, may expose the crop to water stress, especially during grain filling, thereby lowering grain weight and HI (Santosh et al., 2024; Zaman et al., 2017; Nyawade et al., 2021; Koutroubas et al., 2004). Additionally, better sunlight distribution and radiation during the long rains enhance photosynthesis and grain filling, further supporting higher HI (Jamal et al., 2022; Stuerz et al., 2020; Nasar et al., 2023; Maitra, 2020; Maitra et al., 2025b).

Phosphorus uptake in both grain and stover was significantly affected by genotype, with Nerica 4 consistently demonstrating greater uptake across treatments and seasons. This suggests that Nerica 4 has a more efficient root system and higher nutrient-absorption capacity, especially during the short rains, a trait vital in low-phosphorus environments (Sattari et al., 2012). Moreover, Nerica 4 allocated a greater proportion of absorbed P to grains, reinforcing its efficiency in nutrient use and productivity. These findings align with Heuer et al. (2017), who emphasized the importance of uptake and nutrient distribution in improving rice yields.

Interestingly, grain phosphorus uptake was higher during the long rains despite higher grain yields during the short rains, a trend that deviates from the typical positive correlation between yield and nutrient uptake (Fageria et al., 2010). This anomaly may be attributed to increased soil P solubility and mobility due to higher rainfall during the long rains, improving P availability and translocation to the grain (Zhao et al., 2004; White et al., 2009). Furthermore, the extended grain filling period in the long rains may have allowed for increased nutrient accumulation in grains (Veneklaas et al., 2012). The absence of a similar trend in stover P uptake suggests preferential P allocation to reproductive tissues under favorable long-rain conditions (Rose et al., 2011). Conversely, the higher yields but lower P uptake in the short rains may reflect a dilution effect, where higher biomass reduces nutrient concentration per unit mass (Krishna et al., 2024; Ngugi et al., 2022; Jarrell et al., 1981).

Phosphorus use efficiencies comprising agronomic efficiency (AE), partial factor productivity (PFP), recovery efficiency (RE), internal utilization efficiency (IE), and physiological efficiency (PE) varied significantly across phosphorus rates, seasons, and varieties. These variations point to the critical role of genetic traits in determining nutrient utilization. This is supported by several workers (Syers et al., 2008; Wissuwa et al., 2009; Ochieng et al., 2021), who observed that phosphorus use efficiency differs among rice genotypes and directly influences productivity under varying soil fertility conditions.

Among these metrics, AE and PFP peaked at 30 kg P ha^{-1}, indicating this rate as optimal for yield improvement with efficient phosphorus use. Komboka exhibited higher AE and PFP than Nerica 4, highlighting its efficiency in converting applied phosphorus into grain yield, as also noted by Baligar et al. (2001). The decline in efficiency at higher P levels is explained by the law of diminishing returns (Fageria et al., 2013; Alhammad et al., 2023).

Recovery efficiency (RE) was highest at 50 kg P ha^{-1}, with Komboka showing better uptake of applied phosphorus, suggesting reduced nutrient losses and improved use efficiency. Although Komboka outperformed in RE, Nerica 4 achieved a phosphorus recovery efficiency of 64%, attributed to its interspecific genetic makeup (Oryza sativa × Oryza glaberrima), which confers a robust and extensive root system ideal for low-input systems (Saito et al., 2023). These traits, combined with favorable conditions, enable Nerica 4 to realize its genetic potential for high phosphorus uptake and utilization (Haefele et al., 2006).

Physiological efficiency (PE), measuring biomass produced per unit of absorbed phosphorus, was higher in Nerica 4, especially under moderate phosphorus rates, indicating its strong nutrient conversion ability. This aligns with Rose et al. (2013), who emphasized the importance of PE under nutrient-limited conditions. Similarly, internal utilization efficiency (IE), representing

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grain yield per unit of absorbed phosphorus, was significantly higher in Nerica 4 across all treatments, confirming its superior nutrient assimilation and grain conversion capability (Fageria et al., 2011).

The application of 50 kg ha^{-1} 70 kg P ha^{-1} supported optimal performance in both Nerica 4 and Komboka, indicating that these rates effectively meet the crop's phosphorus requirements. Phosphorus plays vital roles in early root establishment, energy transfer (ATP), and grain formation (Hinsinger, 2001). The strong response to these rates reflects the improved nutrient efficiency of these varieties and confirms the agronomic optimum under prevailing conditions. These results align with Buresh et al. (2010), who advocate moderate phosphorus inputs for upland rice systems to ensure high yields without environmental risk.

In summary, phosphorus application significantly influenced upland rice yield and nutrient efficiency, with Nerica 4 showing superior performance across multiple parameters. These findings highlight the potential of phosphorus-efficient varieties in optimizing upland rice productivity, especially in phosphorus-deficient environments. The study advocates for site-specific and genotype-sensitive nutrient management strategies to maximize yield while promoting sustainable agricultural practices. Further long-term research is recommended to validate these findings and integrate efficient genotypes like Nerica 4 into broader nutrient management frameworks, as proposed by Lal (2020).

Conclusion

This study highlights the crucial role of phosphorus fertilization in enhancing rice productivity, with significant interactions between P levels and rice varieties. The superior yield and nutrient uptake efficiency observed in Nerica 4 indicate its greater adaptability to phosphorus fertilization than in Komboka. These findings emphasize the necessity of variety-specific fertilizer management strategies to maximize yield potential and nutrient use efficiency in rice cultivation. Furthermore, the observed variations in phosphorus efficiency underscore the importance of selecting genotypes with superior nutrient-use traits for sustainable rice production. Based on the results, application of 70 kg P ha^{-1} is recommended for farmers targeting maximum yield, particularly when using responsive varieties like Nerica 4. However, 50 kg P ha^{-1} proved more efficient in nutrient use, offering a cost-effective option with relatively good yields. Farmers' goals and resource availability should guide the choice between these rates. The results highlight a trade-off between yield and phosphorus-use efficiency, emphasizing the need for site-specific fertilizer recommendations. We recommend that further research should focus on evaluating long-term soil health and economic returns across varying environments and genotypes.

Conflict of interest

None

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